Dimpled Ball Grid Array Qualification Testing for Space Flight Applications

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Abstract -With smaller and smaller Printed Wiring Board (PWB) form factors, such as CompactPCI®, the need for smaller packages with high I/Os has grown significantly. Thus, the use of Ball Grid Array packages have become necessary for space flight applications. A Jet Propulsion Laboratory/NASA technology and system development program that services various spacecraft missions uses a 3U CompactPCI® form factor. The System Input/Output board requires a large amount of I/Os and has limited area, so conventional packages, such as quad flat packs will not fit. A 472 Dimpled Ball Grid Array (D-BGA) package was chosen for this application. Since this type of package has not been used in past space flight environments, it was necessary to determine the robustness and reliability of the solder joints. The D-BGAs were qualified by developing assembly, inspection and rework techniques as well as environmental tests. The test article was a printed wiring assembly (PWA) consisting of four daisy chained D-BGA packages. Visual inspection of the outer solder joints and real time X-ray were used to verify solder quality prior to testing. The test article was electrically monitored for shorts and opens at or above 1 μs during all environmental tests. Three environmental tests were conducted: random vibration at 0.2 g^2/Hz, pyro shock at 2000g for 50 ms, and thermal cycling from -55°C to 100°C for 200 cycles. After testing, Scanning Electron Microscope (SEM) analysis was performed on various D-BGA cross sections to determine the quality of the package-to-board interface. The 472 D-BGA packages passed the above environmental tests within the specifications and are now qualified for use on space flight electronics.

INTRODUCTION

This paper summarizes the results of the qualification testing of a 472 Dimpled Ball Grid Array (D-BGA) package for space flight use. The test consisted of assembly, rework, and inspection techniques. Environmental tests such as random vibration, pyro shock, and thermal cycling were conducted on a flight like configuration.

TEST CONFIGURATION

The part being qualified was a 472 Dimpled BGA package. D-BGAs are similar to regular BGAs with a small column, or dimple, between the ball and the package, see Figure 1. The D-BGA package was chosen since its reliability margin was higher than standard BGA packages or even Column Grid Arrays. The packages were internally daisy chained and balled by Honeywell. The majority of the D-BGA packages had Sn60/Pb40 solder balls, with a small portion having Sn46/Pb46/Bi08 solder balls for comparison.

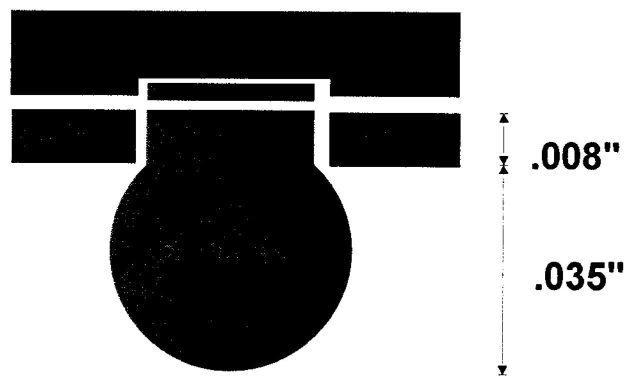

Figure 1. Solder joint on a Dimpled BGA

The board was designed using non solder mask defined pads for the D-BGAs. The PWB was 6 layers with simulated ground planes and was 0.080" thick. Two different board materials were used to see if their CTEs would effect the solder joint reliability. There were total of 7 polyimide (Polyimide-glass per IPC-4101/40) and 3 Aramid (Aramid polyimide per IPC-4101/53) PWA's.

The test article was a printed wiring assembly (PWAs) with two to four D-BGA packages, see Figure 2. The PWA was designed to represent a 3U CompactPCI® slice. See Table 1 for PWA test designation. The test PWA was designed such that when the D-BGA was attached, four daisy chains per package were formed.

Part of PWB daisy chain is shown in Figure 3. Dummy parts were placed on the backside of the PWA to simulate a double sided assembly. The D-BGAs were placed on the PWB in the approximate locations as flight. The thermal cycling PWAs had test connectors installed on the board for electrical monitoring. The shock and vibration test boards had wires soldered to the board for electrical monitoring. These board also had heat sinks, Card-locs, CompactPCI® connectors, and a front panel.

An Aluminum, six slot flight-like chassis, with a mounted backplane was used for the shock and vibration tests. There were five PWAs installed in the chassis, two of which were D-BGA boards. The test axes and accelerometers are shown in Figure 4. The backplane was a six slot, 3U, PWB (see Figure 5) with installed CompactPCI® connectors. Its design was based upon the CompactPCI® specification PICMG 2.0 R2.1.

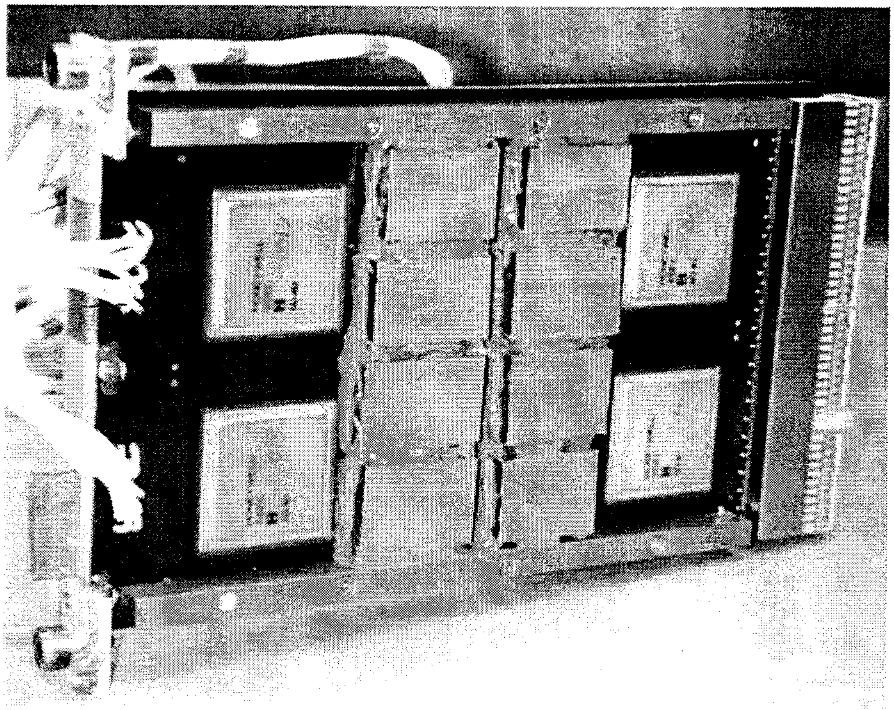

Figure 2. D-BGA Test Assembly

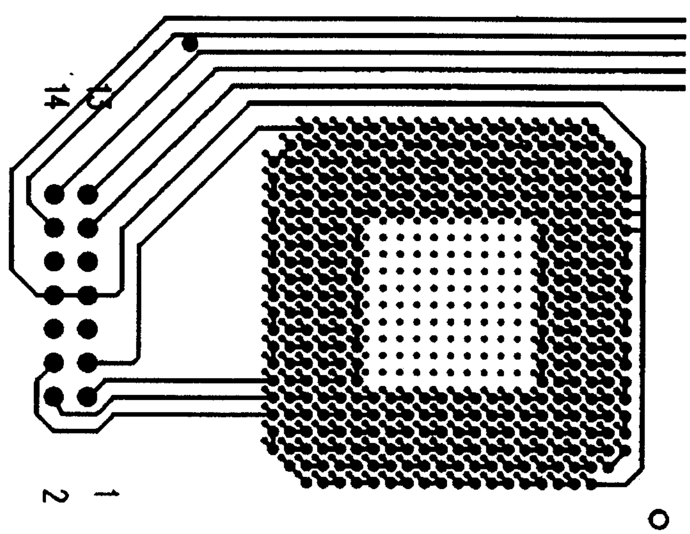

Figure 3. Art work on PWB

Table 1. SIO D-BGA Assembly Matrix

S/N	Ball Type Qnty. (ea)	PWB Material	Test	Comments
1	2, Sn60/Pb40	Polyimide	Thermal Profile	
2	2, Bi Based	Polyimide	Thermal Profile	
3	2, Sn60/Pb40	Polyimide	Thermal Cycle/ 1 sec electrical monitoring	Cross Sectioned @ 150 & 200
4	2, Sn60/Pb40	Aramid	Thermal Cycle/ 1 sec electrical monitoring	Cross Sectioned @ 200
5	4, Sn60/Pb40	Polyimide	Removed DBGAs	Cold solder joints. Relfowed twice. Some columns. See Section XX
6	4, Sn60/Pb40	Aramid	Shock & Vib	Some cold joints.
7	4, Sn60/Pb40	Polyimide	Thermal Cycle/ 1μ sec electrical monitoring	Some solder columns.
8	1, Sn60/Pb40	Aramid	New Thermal Profile	Used 1 new plus 3 dummy DBGAs
9	4, Sn60/Pb40	Polyimide	10 Thermal Cycles Shock and Vib	New PWB with additional solder mask. Qual.
10	4, Bi Based	Polyimide	Thermal Cycle/ 1μ sec electrical monitoring	Will be used for comparison

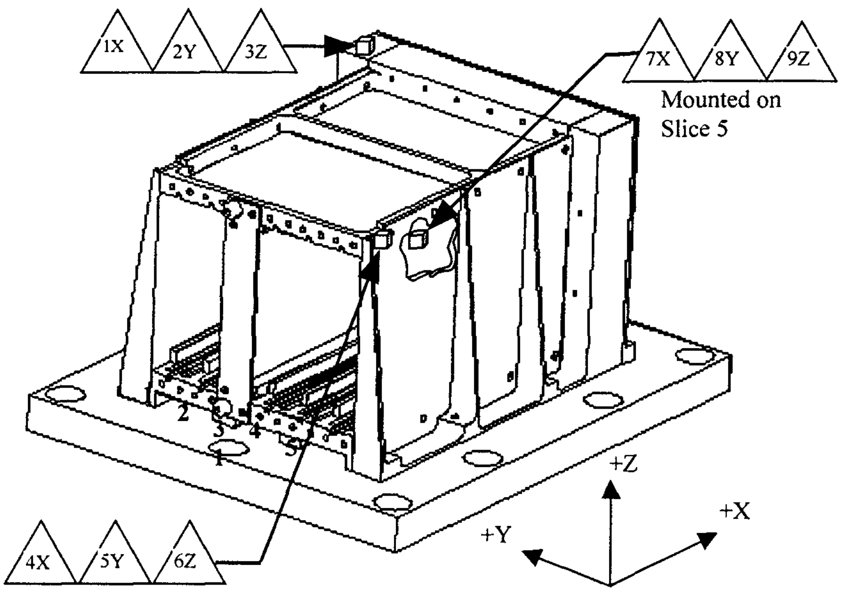

Figure 4. Vibration & Shock Test Chassis

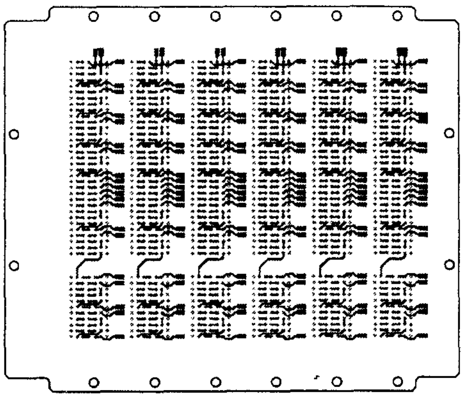

Figure 5: Six-Slot Vibration Test Backplane

ELECTRICAL MONITORING SYSTEM

Voltage is read across a sense resistor (97.5 ohms) by a differential measurement of two buffer amplifiers. This differential voltage is used to drive the photo-diode of the opto-coupler, which converts the analog measurement to a digital signal. When the differential voltage drops below 2.4 volts the diode gets voltage/current starved and the output from the opto-coupler transitions to a digital high (5 volts), indicating that the daisy chain circuit has gone to a high impedance state. The value of the daisy chain impedance at which the circuit transitions to open can be found in Table 2 below. When the resistance value of the daisy chain is below the chosen value found in Table 2 the opto-coupler output is LOW or 0 volts. The state (HIGH or LOW) of the daisy chain is captured by the RS Flip-Flop circuitry made up of two NOR gates. Once the opto-coupler output transitions from HIGH to LOW the Flip-Flop circuit captures the transition. This "memory" allows the data acquisition computer to leisurely read the outputs from all data channels. Once the computer has finished reading the data channels, supplying a +5 Volt pulse to the RESET line will reset the system. The nominal input of the RESET line must be LOW to ensure proper operation. At start-up the RESET line must also experience this +5 Volt pulse in order to bring the Flip-Flop into a known state. Acquisition times, daisy chain resistance's and Daisy chain voltage plus (+) V_{R98} set points can be found in Table 2 below. As can be seen in Table 2, different intermittent time resolutions from 1 microsecond to 4.1 microseconds can be programmed into the system by varying the input voltage (Voltage across daisy chain and R). For proper operation the Daisy Chain must be put in series with resistor R.

Table 2. Experimental results of Intermittent Detection Circuit.

Colapse Voltage 2.4 V

Voltage	Trip Time (μs)	Trip Res (ohms)
3	1	27
3.5	1.8	48
4	2.6	71
4.5	3.3	90
5	4.1	112

ASSEMBLY

Pre Assembly and Inspection

All PWBs and D-BGAs were visually inspected under a microscope at 10X to 20X for defects such as:

- Damage to board material or circuitry
- Proper solder mask application on PWB
- Discoloration or delamination of board material
- Missing or damaged pads
- Missing or damaged balls on D-BGA
- Damage to D-BGA package
- Solder Ball cracks

The first batch of PWAs assembled did not have solder mask on the vias and traces directly connected to D-BGA pads. The second batch of boards were procured with solder mask on the vias and traces. See Figure 6. A coplanarity check was performed on the D-BGA parts with a maximum delta in the height of 0.004". See Table 3 for typical coplanarity data. The PWB was checked for solderabilty using a SERA tester. The D-BGAs and PWBs were tested for continuity (open and short test) prior to assembly to assure the integrity of the daisy chains. The PWBs were cleaned in an ECD 7300 batch cleaner using a DI water soponifier wash cycle and a DI water and isopropyl alcohol rinse, then vacuum baked at 100°C ± 10 °C for 8 hours.

Table 3. Coplanarity Data

	POLYIMID S/N 003		ARAMID S/N 004	
ZONE	BGA S/N 007	BGA S/N 008	BGA S/N 004	BGA S/N 010
1	0.1370	0.1348	0.1420	0.1428
2	0.1407	0.1389	0.1468	0.1502
3	0.1450	0.1422	0.1541	0.1572
4	0.1451	0.1408	0.1532	0.1600
5	0.1491	0.1439	0.1559	0.1605
6	0.1465	0.1399	0.1512	0.1553
7	0.1417	0.1357	0.1435	0.1491
8	0.1391	0.1335	0.1441	0.1451

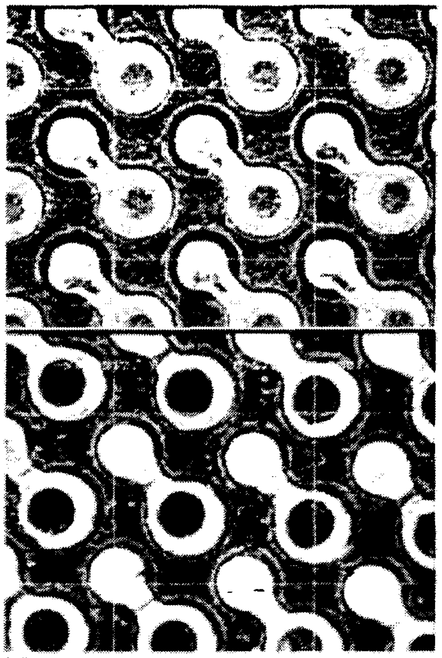

Figure 6. Solder Mask

Assembly Process

Thermal profiles were run using a sample board and similar components in order to develop a vapor phase solder reflow profile. The key factor was to measure the temperature gradient underneath the D-BGA, since it is the last one to reach the desired temperature. With the first profile the preheat temperature of D-BGA was measured to be 110°C, which was lower than the expected temperature of 140-160°C. The dwell time above liquidus (183^{0}C) was 140 seconds, which was higher than the desired 90-110 seconds. Adjustments in preheat temperature, dwell time and reflow dwell time were made and a new profile was run. The preheat temperature reading was 133^{0}C, which was very close to the expected temperature, and the dwell time above liquidus was 134 seconds. The dwell time in the vapor zone was reduced and a final profile was run that resulted in the correct temperature and dwell time, see Figure 7.

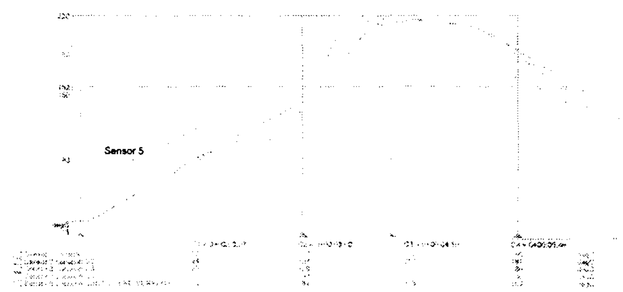

Figure 7. Relfow Profile

A Sn 63 solder paste with RMA flux was used on both sides of the PWB and was deposited using a 7-mil thick stencil. Dummy SOICs were placed on backside of the PWB using an automatic pick-and-place machine and the D-BGAs were placed using a split vision AIRVAC rework system. The solder paste height was measured using a 3-D Laser inspection system. The assembly was soldered in a vapor phase reflow system using the above profile. The PWAs were cleaned as follows: cleaned in an ECD 6307 batch cleaner using a Terpene solvent; cleaned in an ECD 7300 batch cleaner with DI water, soponifier and rinsed with DI water followed by isopropyl alcohol; then tested in an ionograph for ionic residues.

Final Inspection

The outer solder balls were visually inspected using both a conventional microscope and also an ERSAscope optical inspection system, see Figure 8. The assembly appeared to be free of residue and the outer rows showed good wetting. Real time X-ray was also used to check for missing solder balls, shorts, voids, pad to ball alignment and reflow problems. Figure 9 is an example of one of the X-rays.

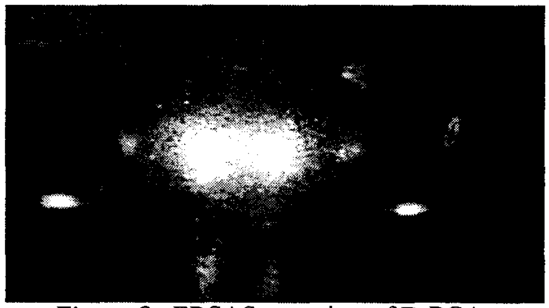

Figure 8. ERSAScope view of D-BGA

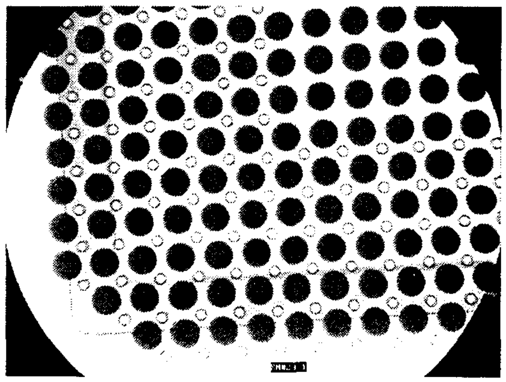

Figure 9. X-ray of D-BGA

ENVIRONMENTAL TESTS

Electrical continuity tests were performed with a Fluke meter to assure integrity of all soldered connections before and after each test. All environmental tests were electrically monitored continuously for shorts and opens above 1 μs during testing.

Thermal Cycling was performed using the following profile:

- Temperature High End: 100°C $\pm$ 2°C
- Temperature Low End: -55°C $\pm$ 2°C
- Dwell at maximum temperature: 1/2 hour minimum
- Dwell at minimum temperature: 1/2 hour minimum
- Transition rate (high-to-low and low-to-high): $\leq$ 5°C/minute

S/N 003 and 004 were thermal cycled to 200 cycles. The Polyimide (S/N 003) board had a D-BGA part cross sectioned at 150 cycles and one at 200 cycles. The Aramid board (S/N 004) was cross sectioned at 200 cycles. S/N 007 was thermal cycled for 300+ cycles, and will continue to be cycled until a failure occurs. S/N 009 was also thermal cycled for 10 cycles before going to the Shock and Vibration tests. S/N 010 has seen over 20 thermal cycles with no intermittents and will continue until failure occurs.

The random vibration test spectrum is defined in Table 4. The higher-level (severe) random vibration test spectrum is defined in Table 5. The test spectrum for the low level sinusoidal survey test is provided in Table 6. The low level sinusoidal survey test was performed to assess the structural integrity of the PWA and to gain insight into the modal characteristics of the assembly.

Table 4. Initial Random Vibration Test Spectrum

Frequency Range (Hz)	Qualification Test Level
20	0.032 g^2/Hz
20-50	+9 dB/octave
50-250	0.20 g^2/Hz
250-350	-6 dB/octave
350-1000	0.10 g^2/Hz
1000-2000	- 12 dB/octave
2000	0.0063 g^2/Hz
Overall	12.3 g_{rms}
Test duration: Three minutes per axis	

Table 4. Severe Random Vibration Test Spectrum

Frequency Range (Hz)	Protoflight Test Level
20	0.032 g^2/Hz
20-70	+6 dB/octave
70-300	0.40 g^2/Hz
300-400	-6 dB/octave
400-800	0.20 g^2/Hz
800-2000	- 9 dB/octave
2000	0.0129 g^2/Hz
Overall	16.7 g_{rms}
Test duration: Three minutes per axis	

Table 6. Sinusoidal Survey Test Spectrum

Frequency Band (Hz)	Test Level
5 - 2000	0.25 g 0-to-peak

Sweep Rate = 2 octaves per minute; One upsweep per axis

The PWAs were subjected to three pyroshock pulses in each axis, to simulate launch conditions. The shock waveform needed to satisfy both of the following criterion: A) be oscillatory in nature, and B) decay to less than 10% of its peak value within 50 milliseconds.

To minimize over testing of the assembly, manual notching was imposed on the system at the natural resonance of the chassis during the Y axis and Z axis vibration test. The justification for this manual notch is based on an estimate of how the unit would respond when mounted to a flight-like support panel. If force limiting techniques were used, it is estimated that at least a 12 dB notch would have been observed. To that end, a manual notch was imposed at the natural frequency of the unit (544 Hz in Y; 1000 Hz in Z) for high level vibration runs. Without the manual notch, the electronics boards would have seen over 297 G's of load in the Z axis test and 181 G's in the Y axis test, which is too high for an assembly of this size.

TEST RESULTS

S/N 008 was used as a thermal profile board and was also used as a control sample for cross sections. Figure 10 shows how the samples were cut from two sections. Figures 11 and 12 show typical cross sections of the control sample. These cross sections indicated that there is a small amount of separation between the dimple and the package.

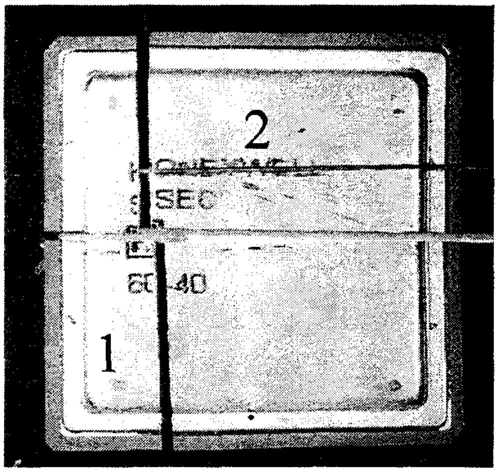

Figure 10. D-BGA Cut into Pieces #1 and #2

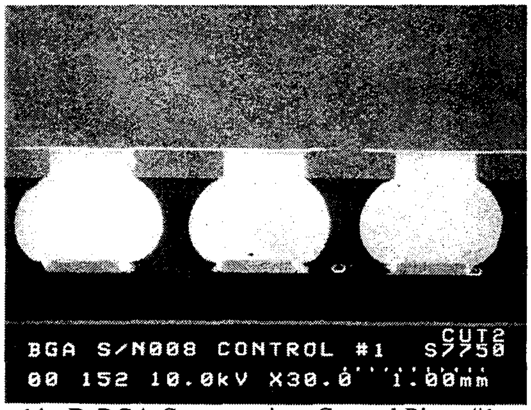

Figure 11. D-BGA Cross section, Control Piece #1

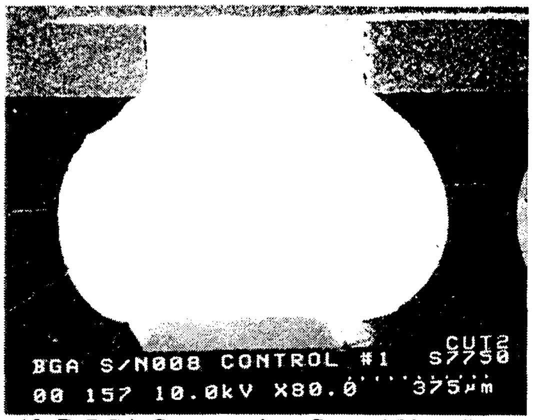

Figure 12. D-BGA Cross section, Control Piece #1a

Thermal Cycling

All thermal cycle tests were conducted with no intermittents. The cross section data indicates some signs of cracking or separation at the point where the solder ball and the solder mask meet at the PWB. Cross sections were taken on one sample from S/N 003 at 150 thermal cycles. Figures 13 through 15 show an example of the separation between the dimple and the package. It appears that thermal cycling propagates this separation and may be a weak point. Figures 16 and 17 indicate an additional weak point; where the solder ball meets the solder mask. This crack disappears as the cross sections moves to the center of the ball. This will be discussed again further in the paper.

Cross sections were taken on one sample from S/N 003 (Polyimide) and S/N 004 (Aramid) at 200 thermal cycles. Figure 18 is a typical cross section after 200 thermal cycles. Figure 19 shows the same anomalies as mentioned above.

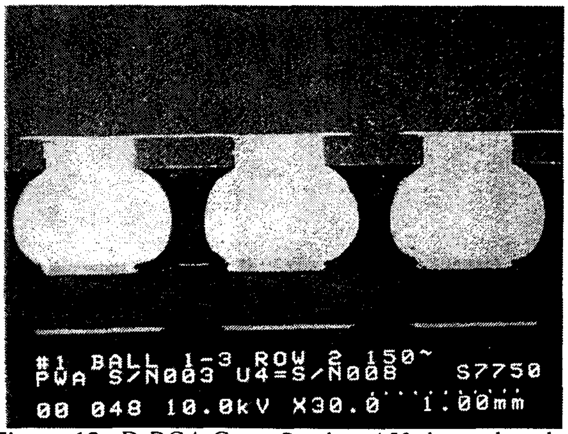

Figure 13. D-BGA Cross Section, 150 thermal cycles

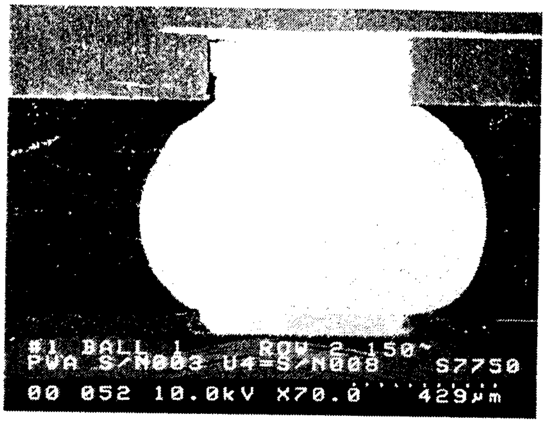

Figure 14. D-BGA Cross Section, 150 thermal cycles

Figure 15. D-BGA Cross Section, 150 thermal cycles

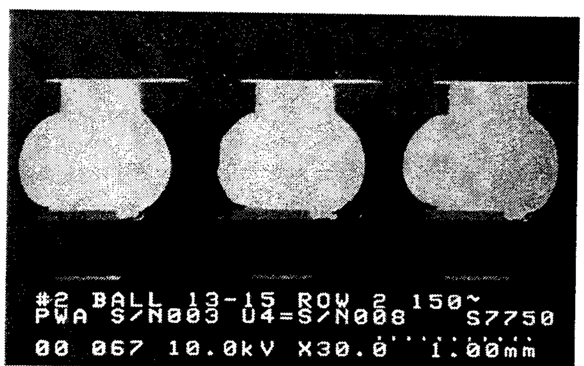

Figure 16. D-BGA Cross Section, Solder mask effect

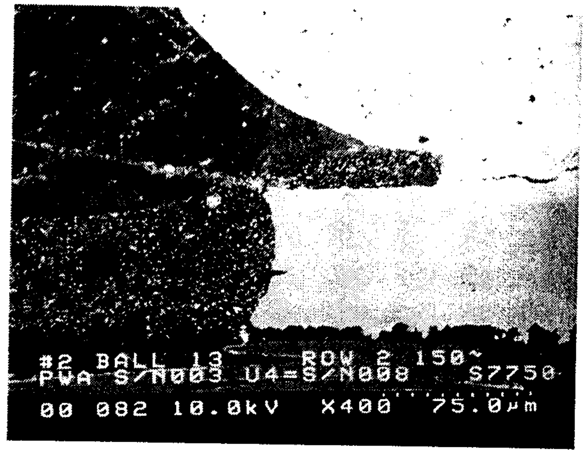

Figure 17 D-BGA Cross Section, Solder mask effect

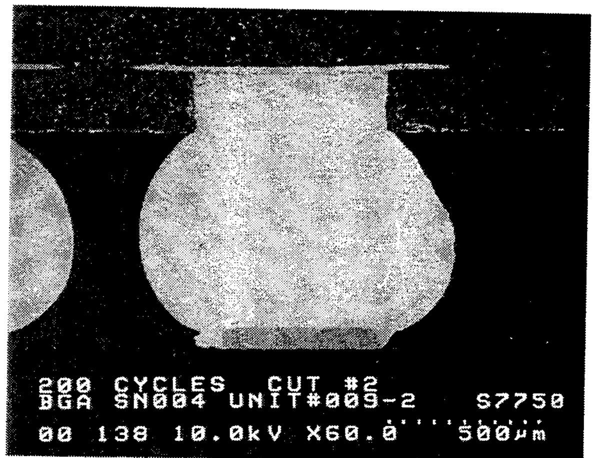

Figure 18. D-BGA Cross Sec, 200 thermal cycles, Typical

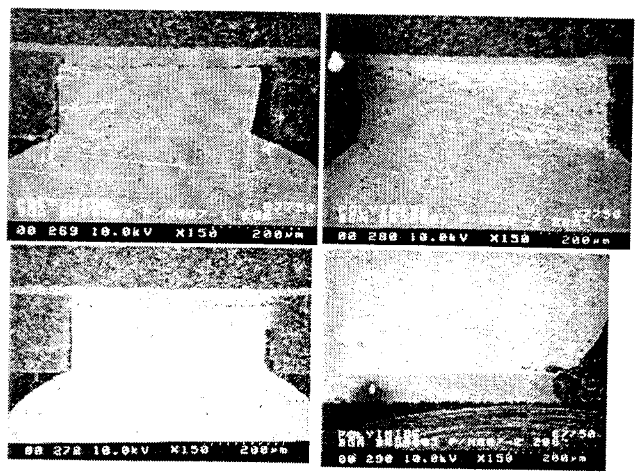

Figure 19. D-BGA Cross Section, 200 thermal cycles, anomalies

Shock and Vibration

The shock testing was completed successfully. The vibration test $0.2g^2$/HZ run on the Z and X axes was run with no intermittents. One intermittent occurred during the $0.2g^2$/Hz level in the Y-axis when a mass mock up piece fell off and hit one of the D-BGAs on S/N 009. The assembly was then tested at the $0.4g^2$/Hz level in all three axis. The severe (0.4 g^2/Hz) vibration caused one intermittent in the other D-BGA test board that had non ideal, or cold, solder joints. No other opens or intermittents occurred during testing.

After the test both D-BGA boards were visually inspected and electrically checked. The outer solder balls were visually inspected and appeared the same as prior to testing. The boards were also X-rayed, and showed no anomalies.

The cross section of the crack caused by the mass impact is shown in Figure 20. There were no signs of solder degradation, which would be evidence of a fatigued solder joint from the vibration test. Figure 21 shows a typical cross section. Cross sections were also conducted on two other parts on S/N 009. The cross sections revealed minor voiding at 500X that were likely caused by oxidation on the PWB pads during the fabrication process, see Figure 22. One part showed slight cracks at the ball to pad interface in a few locations near the corners, while another part had no cracks.

Figure 20. Cross Section of D-BGA A3, Cut 2

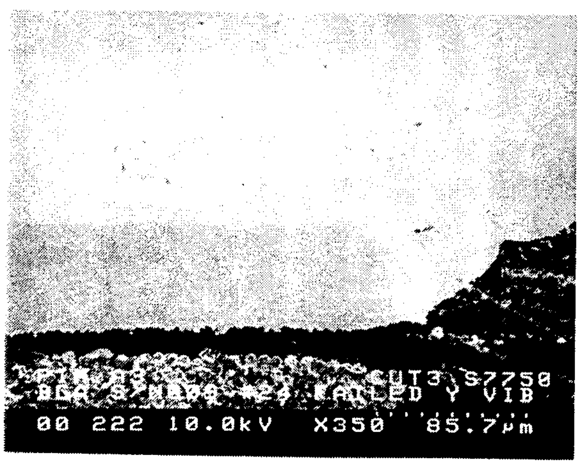

Figure 21. Typical Cross Section of D-BGA

Figure 22. Typical Cross Section, D-BGA, S/N 009-21

CONCLUSIONS

Although there were two intermittent channels during the vibration tests, the cross sections show that D-BGA packages with good solder joints can be used successfully for space flight applications . The one intermittent on D-BGA S/N 006 did not occur until the severe vibration test, and since this PWA did not have ideal solder joints prior to testing it was not considered to be part of the qualification test. The intermittent that occurred during the vibration test, on S/N 009, was caused by the mass mock up falling off. The cross section data shows no signs of solder joint fatigue. The D-BGA solder joints would not have failed unless the cracks were induced by the mock-up piece. The D-BGA packages with good solder joints, and 94% of the marginal solder joints, passed the shock and vibration test requirements. The thermal cycling requirements, up to 200 cycles with no intermittents, was also meet.

A standard D-BGA part with Sn63/Pb37 solder, using JPL's SMT assembly process, survived the thermal and mechanical environmental requirements. The cross section data showed no signs of solder joint fatigue. The 472 Dimpled Ball Grid Array (D-BGA) package is now qualified for space flight use.

ACKNOWLEDGMENTS

The authors wish to give a special thanks to Mike Gross for designing the electrical monitoring system, to Amin Mottiwala for consulting and support, and to Paul MacNeal and Ana Arreola for test engineering support. The research described in this paper was conducted at the Jet Propulsion Laboratory, California Institute of

Technology, under a contract with the National Aeronautics and Space Administration.